THE WORLD OF SOUND

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SIX LECTURES DELIVERED BEFORE A JUVENILE AUDITORY AT THE ROYAL INSTITUTION, CHRISTMAS, 1919

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TO

PEGGY, GWENDY, AND PHYLLIS

WHO DISCUSSED WITH ME SO MANY OF THE THINGS IN THIS BOOK AS WE WALKED TO SCHOOL IN THE MORNINGS

AND TO

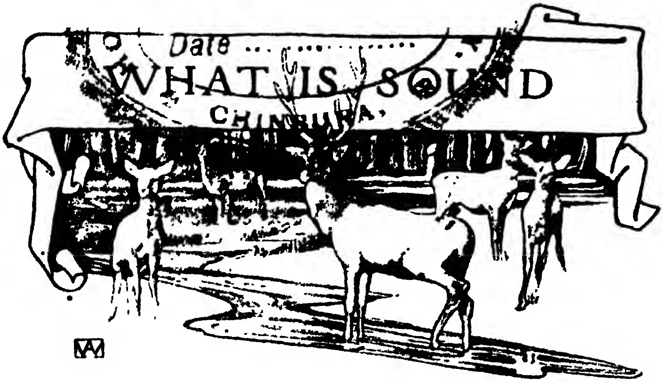
ALL THE OTHER JUVENILES

(INCLUDING THOSE OF THE GROWN-UP VARIETY) WHO CAME TO THE CHRISTMAS LECTURES AND MADE SUCH A KINDLY AUDIENCE

CONTENTS

ILLUSTRATIONS

The decorative headings and tail-pieces to the Lectures, and the pencil vignettes in the text, are reproduced from drawings by Miss Audrey Weber; while the illustrations of the actual experiments are by Mr. W. B. Robinson, from material supplied by the Author.



WHAT IS SOUND

ALL around us are material objects of many kinds, and it is quite difficult to move without shaking some of them more or less. If we walk about on the floor, it quivers a little under the fall of our feet; if we put down a cup on the table, we cannot avoid giving a small vibration to the table and the cup. If an animal walks in the forest, it must often shake the leaves or the twigs or the grass, and unless it walks softly with padded feet it shakes the ground. The motions may be very minute, far too small to see, but *they are there nevertheless.*

Besides the obvious surroundings of material things, there is an ocean of air in which we live. We cannot move without stirring it; and, moreover, whenever we make anything else move, as when we shake the ground or the branches or the

table or whatever it may be, the air is shaken too because it touches all these objects and moves when they move. It is very easy to set the air quivering, and when once a quiver is started it runs through the air in all directions till it has spread and weakened and died away. Also it is a very curious thing that the air can carry ever so many quivers at the same time, going in many different directions, and of many varieties. But each travels as if there were no other there. We will presently consider an experimental illustration of this fact.

Now since nothing can be done without starting shakes and quivers, in solids or in liquids or in air, in some or all of them, and since it is very important to every one to know what is happening round about him, so far as it is possible to do so, it is not surprising to find that we human beings, and most animals, possess organs especially fitted to detect these shakes and quivers, and that we make great use of them. The ear is marvellously sensitive to the minute quiverings that come to it through the air, and then pass down the tube of the ear and come finally to the delicate organs within. We say that we hear a sound, which means that somewhere or other an air quiver has been started and has reached our ears. As the life and processes of the world go on the actions which take place are accompanied by these tremors, and we live in

this world of sound. We can interpret what we hear because all the tremors are different and we have learnt to know them all. We can tell the sort of tremor that is made by the rustle of the leaves from the sort that is made by thunder or the call of an animal. In fact, it seems quite absurd to think that there is anything wonderful in it, because the "sounds seem so different." But of course that is just where the wonder lies; only air tremors in every case, and yet the ear has such marvellous powers that it can sort them all out from each other, can tell one person's voice from another, can tell one word from another, can even tell by the minutely differing shades of inflection the spirit that lies behind the word. The more one thinks about it the more wonderful one finds it to be.

No doubt the reason why ears can be and are so finely trained is because the information they give is so important and so interesting. Sometimes it is a matter of life or death, as in the case of the animal who hunts or of the animal that is hunted. It is everything to us to be able to talk

to our friends, to use our voices, and to set in motion air quiverings that have special meanings to those that hear them. If we walked in the country how much we should miss if we could not hear the birds or the wind or the brook or the passers-by! Think what it would mean to us if we could have no singing and no music. The quiverings of the air, and our ears that hear them, link us closely to the world about us and to our fellow-creatures.

In this first lecture I want to show you some of the things that happen when sound tremors pass from place to place. And first of all we will repeat some of the experiments that Tyndall used to show in this room half a century ago. Perhaps you do not all know that Tyndall was a very famous lecturer on the staff of the Royal Institution. He gave once a series of lectures on the laws of sound, which he illustrated by beautiful experiments. Most of the apparatus which he used is still here, and it will be quite interesting to use some of it once again.

In the basement of this building, two floors below us, there is a powerful musical box. It is playing now, but we do not hear it because none of the quivers which it makes, whether in the air or the floor or the walls, is strong enough to get to us. They cannot come by the air because there are floors and shut doors which they cannot

pass through easily; and they do not come by way of the walls because the quivers which get into the floor and walls are far too weak. But there is a long rod which rests on the musical box and comes up to this room through holes in the floors which are between. Up this rod the quivers come quite strongly; if I put my ear to the rod I can hear the musical box very plainly. There are probably few in the audience who can hear it, and the reason for that is that the rod is so small in cross section that when the quivers reach the end they do not give enough motion to the air. Some bigger surface is wanted which will take the motion from the rod and be broad enough to shake the air over

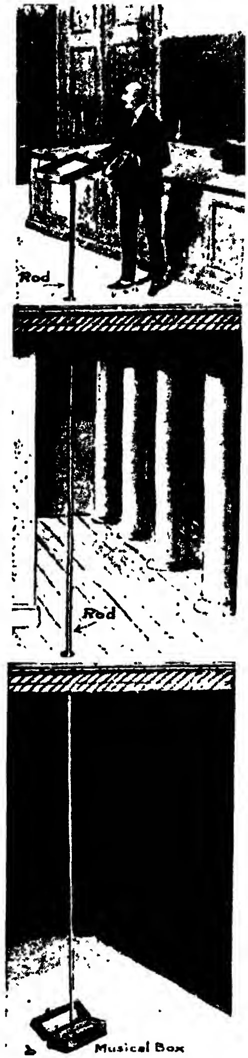


FIG. 1.—Sound vibrations are carried by the rod from the musical box in the basement of the Royal Institution to the tray in the lecture room; from the tray they pass out into the air and are heard by every one in the room.

a large surface. When a tea tray is put on to the top of the rod every one can hear the musical box with ease; a violin does just as well; even a soft felt hat makes the music plain. The chain of communications is now complete. First *of all the springs in the musical box are shaken by the mechanism, then the quivers run into the* sounding-board; they come up the rod, and by means of the broad surface of the violin or other object they are given to the air in such quantity that, even allowing for the spreading through the room, they are strong enough to affect every ear that they reach.

Observe, too, that there is no mistaking the nature of the source; the notes are obviously those of a musical box; the rod, the tray, the violin, the hat, have merely handed on the vibrations, with little change. It is a very common practice, as we shall see later (p. 42), to use a large surface for the purpose of launching enough movement into the air, as we have used the violin.

The experiment we have just made illustrates the passage of sound along a solid body—in this case the long rod. It is easy to find many other examples. The water-pipes in the house often carry sounds. Sometimes there is a "singing" or a "hammer" in the pipes when a tap is opened or closed; and the sound runs along the pipes

into other rooms. We all know the thrilling moments in the stories of adventure when the hero puts his ear to the ground and hears the thudding of the feet of the pursuing horses. In the "string telephones" that have sometimes been so popular, the sound runs along the tightly stretched thread. People who have lost the power of hearing through the air may still in some cases hear music when they rest one end of a rod on the sounding-board of a musical instrument and put the other end to

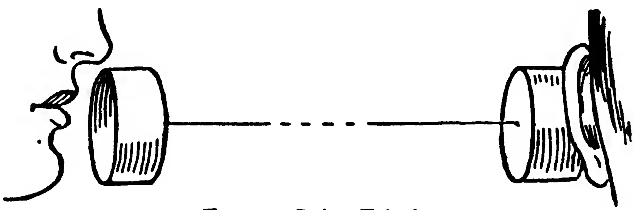


FIG. 2.—String Telephone.

their teeth. The sound runs through the bones of the head and reaches in this way the mechanism of the inner ear, which must of course be uninjured.

Sound can be conveyed by liquids as well as by solids. In some of the experiments carried out for the Admiralty during the war an under-water "buzzer" was used. It is a small water-tight metal case in which a hammer is made by electrical means to rain blows upon one of the sides. When I lower it into a tank of water and put it into action by pressing an electrical key; it sounds out loudly through the room. The hammer in the

buzzer starts vibrations in the metal case, and these run through the water to the walls and so out into the air. The sound has been carried by the water over one part of its journey.

Next we must show the passage of sound through the air, and we will make use of another of Tyndall's famous experimental illustrations. Under this large glass cover there is a clockwork mechanism which can ring a bell. The bell is supported by elastic strings which do not carry sound at all well, so that when it rings, the sound, if it gets to our ears, must have come through the air. The quivers of the bell launch a quivering motion into the air, which gets to the glass wall of the cover and starts it in motion. In its turn the glass shakes the air outside, and the quivers once more run through air and finally reach our ears. Now the cover stands on a plate to which it is firmly waxed down. There is a hole at the centre of the plate which opens into a pipe communicating with an air-pump. The air-pump is worked, and gradually the air is drawn away from underneath the cover. When there is little air left we notice that the sound of the bell has become much weaker. And at last, when every trace of air has been removed, it dies away altogether. That shows that the air was wanted to carry the sound. When we let the air in again the bell sounds out as before.

We have now heard sounds travelling through solid bodies such as the rod that came from the musical box in the basement, through the water in the tank, and through the air of the room, and we have observed that when there is neither solid

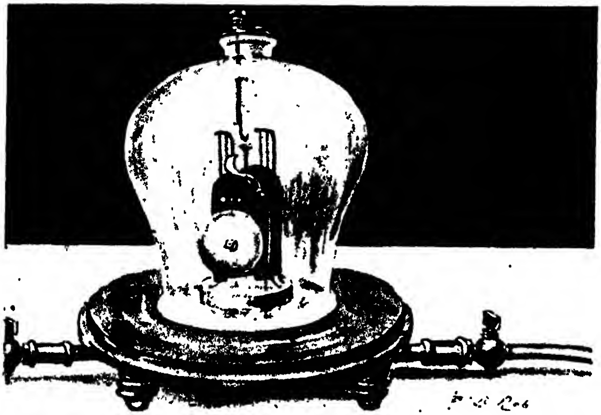


FIG. 3.—Bell ringing in vacuum. The bell is hung by fine threads so that no part of it touches the stand. When the air is removed from the vessel the sound has no path by which it can reach the outside air, and the bell, though seen to be in action, cannot be heard.

nor liquid nor gas, sound is not conveyed at all. It cannot travel across what we call a vacuum. Between us and the sun there is space, more empty of gas or air or any other substance even than the glass container which we used just now. No sound can travel across such a space. Light on the other hand travels quite easily. Light and our eyes that see it deal with the doings of the

whole universe; sound belongs to the world only. I may talk of the universe of light, but I can only talk of the world of sound.

As soon as you understand that sound is a quivering motion which goes from one place to another you will realise that most likely it takes a certain time to make the journey, and so it does. When, for example, a sound travels through the air it takes nearly five seconds to go a mile, and it is a very strange thing that all sorts of sounds, shrill whistles and deep boomings, take just the same amount of time to travel. If a band is playing a long way away, you hear all the instruments keeping time correctly with each other, piccolo and cornet and drum, no matter how far away they are. If some sounds travelled more quickly than others you would only be able to hear music properly when you were quite close to it. It is a very common thing to find examples of the fact that sound takes time to travel. If you are standing on one side of a valley and you watch a train approach a station a mile or two away on the other side, you may notice when the steam first issues in a white cloud from the whistle as the engine-driver gives warning that he is coming; and light travels so fast that you see the steam practically on the instant that the engine-driver opens his whistle. But it may be many seconds before you hear it. I have

often watched the woodcutters at work in Australia, where the clear still air makes it easy to see and hear at long distances. From one side of a wide gully I have seen the strokes of the axe fall noiselessly far away on the other side, and then when the man has straightened himself and begun to move away, the noise of the blows has reached my ears. If you watch a long procession going along a street, marching to the music that heads it, every man puts his foot down at the beat of the drum, but of course the rear ranks do not hear it as soon as the front ranks, so that really they do not march in step. If you look sharply you will see a ripple run along the line as the heads go up and down slightly to the movement of the feet.

Sound travels at different rates through different substances. For example, it travels about fifteen times as fast through iron as it does through the air. You can make an experiment on this in the Park, or anywhere else where you can get a long uninterrupted stretch of iron railing. If you put your ear to the railing and get a friend to strike it with a hammer a hundred yards or so away, you hear the sound twice; first it comes by the iron and afterwards through the air. In water sound travels about four times as fast as in air. It has been necessary, as we shall see later, to measure this velocity very carefully during the

war. In the air the actual rate is nearly eleven hundred feet per second.

As the pulses go to greater and greater distances from their source they spread over wider and wider surfaces and become weaker. The farther away the source of sound is from the listener the feebler it seems to be. But, if we wish to do so, we can prevent the sound from spreading itself over wide surfaces, and it will then carry much farther, as, for example, when we use speaking-tubes, which carry the sound pulses with little loss for quite considerable distances. The walls of the tubes inside ought to be smooth, because, if they are not, the rubbing of the air against the walls, as it moves to and fro when the quivers pass over it, spoils the true shape of the waves, turning them into little whirlpools in which the energy is wasted. Moreover, there must be no sharp corners, no right angles in the tubes, because at a corner some of the sound is reflected and goes back the way it came. When a man uses a speaking-trumpet he does something of this kind also, because the trumpet tends to direct the sound in the way the speaker wants it to go. But the action of the speaking-trumpet depends more on the fact that the speaker can actually get a greater amount of sound out of his own throat. You feel that you are working harder when you are using one. The rigid walls of the trumpet do not allow the sound waves to spread

sideways very readily, and, in a sense, hold them for the vocal organs to work on.

When the sound spreads away without the artificial confinement of a speaking-tube or anything of that kind it is sure to run up against obstacles of one kind or another. What happens to it then is really a subject of great importance. I think you will find it easier to understand this and many other problems connected with the spreading of sound waves if you take the analogous case of waves on the surface of water. If you watch what happens to ripples in various cases you will be much more able to understand what happens in the case of sound.

Here is a ripple tank made for the purpose of such experiments. It is a shallow trough about a yard square, with a plate-glass bottom, filled with a thin layer of water about a quarter of an inch deep. Underneath it on the floor is a naked arc light. The light comes up through the tank and then falls on a sloping mirror [1] which reflects

[1] The mirror is not necessary when there is a flat ceiling, on which the ripple movements can be followed by the audience without difficulty.

it on the wall. Any ripples which are made on the surface of the water show like lines of light and shade on the screen. If I touch the water with my finger, circular ripples spread away just as you have often seen them do when a stone is dropped into a pond. The ripples fade away as the circles become wider. So does the energy of *the sound die* away as it spreads from its source, and even faster than the ripples do on the water. If I touch in two places at once, two sets of interlacing ripples start out. Notice at once how each set goes on its own way right through the other set, as if it was not there. Probably you have noticed this effect also on the surface of a lake or the sea. This is really a point of the very greatest importance to us, for it means that in the case of sound any number of sounds can use the air at the same time, which is a much more wonderful thing than one is apt to imagine at first sight. Suppose it did happen that when a sound was travelling across a certain air-space no other sound could go that way at the same time, or suppose that two or more sounds when trying to cross the same place at the same time had some effect on each other, what a complete confusion of all speech and sound there would be! No ear could ever disentangle it. It is therefore a most remarkable and important thing that however much sound is crossing an air-space a new

FIG. 4.—The Ripple Tank.

sound can find its way across that space just as easily as if no other sound were there. I do not say, of course, that the ear, which has already been filled with various sounds, will be as sensitive to a new sound as if there had been silence until the new one came.

Next we notice in the ripple tank that waves are reflected at the boundaries of the tank. Sometimes we see this effect on the shore of the sea or of a lake, or in the bath, but here it is shown more regularly. If I produce a succession of waves following one another at steady intervals, the reflections and the original waves acting together cover the surface of the water with a beautiful diamond-shaped pattern whose motion across the screen is quite interesting to follow. The original waves and the reflected waves are equally inclined, as you see, to the reflecting surface. This illustrates a very important phenomenon in sound, or for that matter in any other form of wave motion. Waves beating

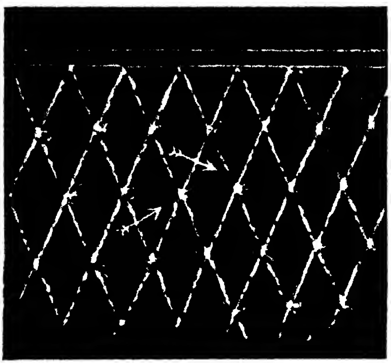


FIG. 5.—A Diamond-shaped Pattern formed by the interlacing of ripples and their reflections.

up against a plane surface are thrown back in such a way that the new lines of waves make the same angle with the surface as the old. This is really the essential property of the ordinary mirror or looking-glass, by which you see behind it an " image " of objects which are really in front. The light-waves that roll up against the mirror from the source in front are thrown back and seem to us to have come from behind. The same effect occurs with sound waves, and then we speak of hearing an echo, especially when the reflecting surface is so far away that we hear the echo some time after the original sound is made, so that the reflection is heard separately and distinctly.

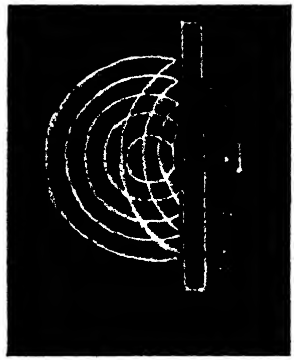


FIG. 6.—A set of ripples and their reflection from a wall. The reflected ripples seem to be spreading outwards from the point I on the other side of the wall. The point I is called the "image" of the source.

Another very pretty way of watching reflection in the ripple tank is to set down in it a wooden square, enclosing a little pond. If we jerk the wooden square, waves roll backwards and forwards from side to side and make a pattern on the screen like a Scotch tartan.

Keeping the square at rest and touching the water

at some point inside it, we get circular ripples which are reflected at the sides. Notice how the reflected ripples are also circular, but that their centre is on the other side of the wall which has reflected them, and just as far behind it as the starting-point was in front. The centre is the "image" of the real source, and is denoted by the letter I in the figure.

A curved surface has very special properties. Here is a piece of brass shaped into the form of a parabola. If I roll a wave into the mouth of it, observe how the waves are gradually turned into circular waves moving in on to their centre; the point on which they converge is called the focus of the parabola. If I dip my finger into the water at the focus, exactly the reverse effect takes place: circular waves spread out from the point, which are converted by the parabola into waves with a straight front. You know that bicycle lamps and motor lamps are often made with parabolic reflectors, and that the light itself is put at the focus; the light is thus sent out in a straight shaft without spreading. Curved surfaces like this have the power of concentrating waves on to particular points. So

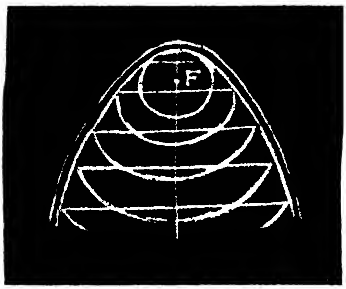


FIG. 7.—Reflection by a Parabolic Mirror.

in some of the great reflecting telescopes the parabolic mirror gathers the light from a star and focuses it on to the field of view of the observer, who studies it there through the " eyepiece."

Here is a block of wood with a long row of nails sticking out from it like a rake. When this row of nails is put into the water in place of the blocks which I was previously using as reflectors, you will notice that most of the energy of the waves passes through and between the nails, but it is clearly seen that a little of it is reflected. There is an interesting parallel in the case of sound. Sound

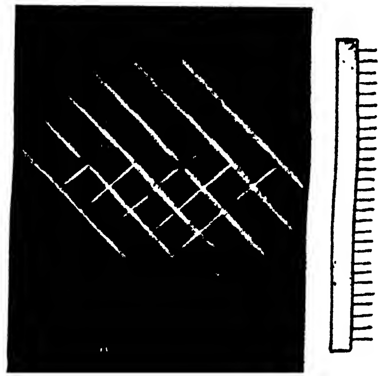


FIG. 8.—A Row of Nails reflects feebly.

is reflected, not only from a flat and complete surface, but even from a set of iron railings or from the foliage of a tree. So when you are driving along in a motor-car you can often hear reflections from the fences and hedges that you pass. If it is a long way to the hedge on either side, there is much less noise than when the hedges close in on you. There is a sudden change in the nature of the sound when you have been running between,

let us say, steep banks and come to an iron railway bridge, or to a paling fence If there is a row of posts that you pass you can notice that each sends to you a little special reflection, so that you get as it were a regular succession of whispers[1] into your ear.

If we dip the nails simultaneously into the

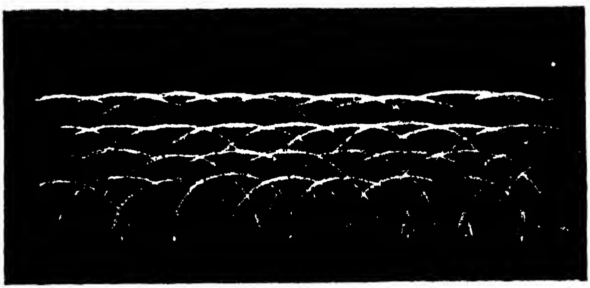


FIG 9.—When a Row of Nails is dipped simultaneously, the many sets of circular ripples join finally into a straight ripple front.

water, each nail starts circular ripples, and the many sets join finally into a straight wave. When you come to a deeper study of optics you will find in this pretty experiment an illustration of what is known as the principle of Huyghens.

I am presently going to put aside the ripple tank and take up another means of following the behaviour of sound-waves. But we need one last experiment with the tank in order to explain

[1] A "whisper" consists mostly of high-pitched notes, and it is such that are reflected in this way.

the reason for our change of course. Notice that when a set of ripples moves past the edge of an obstacle they swing round it. If we put two blocks of wood side by side so as to leave a little opening or gate and roll up waves against the gate, the portion that gets through opens out at once into semicircular waves which fill all the space on the other side. So does a great ocean-wave surge through the narrow opening into a harbour, sending in a disturbance which spreads and fills the harbour with commotion. This thing always happens when the length of the wave is as large as the opening of the harbour, or indeed in any way comparable with it. But if I open the gate in the ripple tank and make waves succeed one another very quickly so that the ripples are now much closer together than the posts of the gate, then there is really a stream of waves across the tank which does not spread to left and right anything like so much as before. The walls have, as it were, cast a definite shadow. You will often see this at the

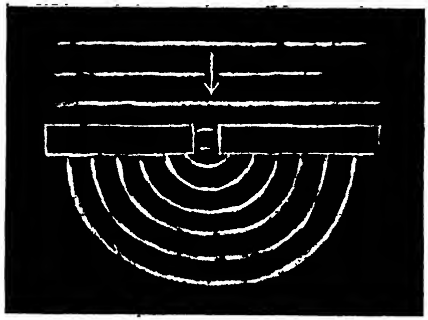


FIG. 10.—Ripples passing through a narrow gate between two blocks and opening out into semicircles.

mouth of the harbour when a gentle wind blows in ripples which carry forward in a stream some way within the entrance.

Exactly the same thing happens in the case of sound, where the long waves, which, as we shall see later, give deep notes, sweep round corners easily. It is the tiny waves, *i.e.* the very high notes, of which alone shadows can be cast by objects of ordinary size

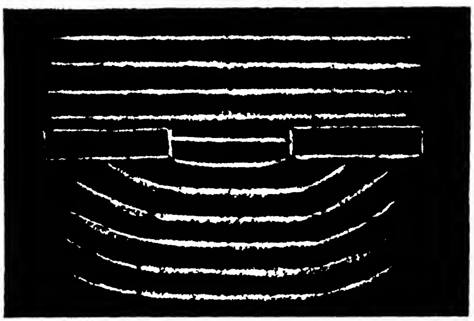


FIG. 11.—When the gate is wide there is more evidence of shadow cast by the blocks.

In this next series of experiments we are going to use sound-waves themselves; but we cannot with any satisfaction use ordinary sound. The distances between the successive waves of such sounds as the voice, or the note of an organ-pipe or a tuning-fork, are anything from one to several feet. If we tried to block them by obstacles or turn them by reflecting surfaces, they would scarcely obey us at all: the waves swing round

obstacles which are of the same size as the distances between the waves, just as the ripples did in the tank. If we are to handle actual sound-waves, they must be such as belong to high-pitched sounds.

It is a very old question this; one of the great questions of Physics, one which troubled Newton himself. He found it hard to admit that light might consist of waves of any kind, because he thought that if it did, the waves should be able to swing round the edges of obstacles—that we should in fact be able to see round the corner, just as we can hear round the corner. A light on one side of a screen cannot be seen from the other; but the voice of a speaker can be heard when the light he is holding is invisible. The explanation lies in the fact that the wave-length of sound is a matter of feet, whereas in the case of light it is a matter of hundred-thousandths of an inch. So the light-shadows are sharp and definite, but sound-shadows are apt to be vague and partial.

We must, then, use very high-pitched sounds if we are going to carry out experiments with rays of sound in this room, and the higher the pitch the better, because high pitch goes with short waves. We will therefore use a whistle so high in pitch that probably it is out of range for most people in this room: they will not hear it at all. But here is a so-called sensitive flame. Gas is

forced under great pressure (eight to ten inches of water) along a narrow tube, from which it emerges through a very small circular nipple into the open air, where it burns in a tall, narrow flame. It is on the point of flaring. If the pressure on the gas were increased a little more the gas, in its hurry to get out, would churn itself up into little whirlpools, mix with the air and burn in a noisy blue flame.

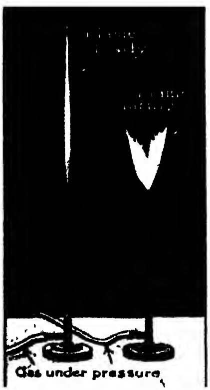


FIG. 12.—The Sensitive Flame.

But not only will extra pressure cause this to happen; any high-pitched sound will do the same. It appears that such a sound disturbs the even flow of the gas *just where it comes out of the nipple*, so that in this case also the turbulent flow and the mixing with the air give the blue flaring flame. Here are the whistles so high in pitch that they are difficult to hear, but you see that they affect the flame even though I go as far away from it as I can and blow the whistle gently—at each blast it ducks in the most marked way. If anybody in the room will drop one coin on another or rattle a bunch of keys, the flame will respond instantly. Every time the letter "s" occurs in what I say the flame responds. All these sounds are essentially of high pitch. Here then we have

a flame sensitive to the very sounds which we want to use, and to them only. Tyndall used this sensitive flame largely, and I believe that some of the apparatus on the table is just as he left it and as he described it in his book on Sound.

The specially high-pitched whistle, known as a "bird-call," was not known to him, but the late Lord Rayleigh made great use of it. It consists of two pieces of thin metal, brass or tin, perhaps half an inch across, placed parallel to one another at a distance of a tenth of an inch or even less. Two very small holes, perhaps a fiftieth of an inch in diameter, are bored through the two parallel pieces so as to face one another exactly. This arrangement is now soldered on to the end of a piece of brass tubing, and a steady stream of air is forced along the tube in order to sound the call. These dimensions can be varied considerably; the smaller they are, and the finer the holes, the higher is the pitch.

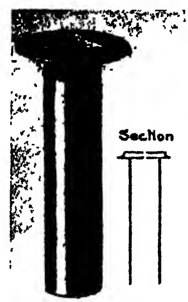


FIG. 13.—The Bird-Call.

The tube is half an inch in diameter.

With a special piece of apparatus, due to Tyndall, consisting of two tubes hinged together (Fig. 14), it is easy to show the reflection of sound. The waves come down one tube, and if any suitable object is placed as a reflector they are thrown back along the other

and cause the flame to flare. You will see that a board or a piece of glass or a sheet of paper can all reflect these sounds. A piece of linen does not reflect much until it is wetted, when it becomes quite a good reflector.

In these experiments we are doing with the waves of sound exactly what we did with ripples in the tank, causing them to be *reflected* at flat surfaces.

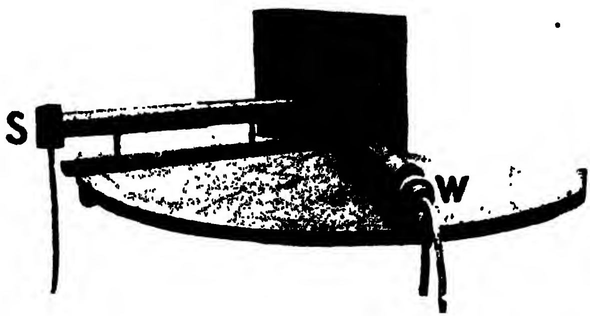


FIG. 14.—The Tyndall Reflecting Apparatus. W, High-pitched whistle; R, Reflector; S, Sensitive flame.

There is another way in which the reflection of waves by a flat surface can be shown very easily. First of all consider this curious property of the sensitive flame which Rayleigh described and found very useful. It is not equally sensitive to sounds coming from all directions; this particular flame is deaf to the whistle when I place it in position A (Fig. 15), and very sensitive when I turn it round to position B. The peculiarity is probably due to some irregularity in the shape of the nipple. Let

us place it in the first of these two positions so that it no longer responds to the bird-call. When I hold the mirror in the position shown in the figure it responds readily, because a reflected beam of sound is being thrown upon it.

A still more striking experiment shows the reflection by a curved mirror. Here is a concave or hollowed mirror (Fig. 16) which is used to reflect light and to focus it upon a point: we will use it to focus both light and sound. We place an electric lamp just over the bird-call, and mount a piece of paper just below the sensitive flame. I stand quite a long way from both bird-call and flame, which latter I have put into the position which is insensitive to the direct action of the whistle, and hold the mirror so that it collects a bundle of light-rays from the lamp and focuses them on the paper. When this is done the sound-waves from the bird-call are focused on the nipple whence the gas issues, which is, as I have said, the sensitive point of the flame, and so, you see, it flares violently.

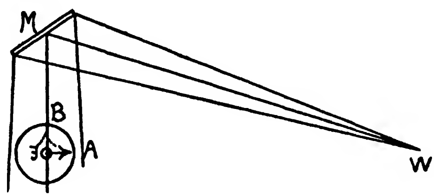


FIG. 15.—Plan of Reflector Experiment. The sound from the whistle W is reflected by the mirror M and acts on the sensitive flame. The flame is so placed as to be sensitive to sound coming from the direction of the mirror, but not to sound coming directly from W.

The least movement of the mirror up or down, right or left, so that the light no longer falls on the paper, and the flame rises up and becomes silent again.

There is one more experiment which I should like to show: a little more difficult to understand, but it is a beautiful one and very few people have seen it. It is due to Lord Rayleigh. I turn the flame so that it is not entirely deaf to the bird-call and

FIG. 16.—Reflection of Sound by Concave Mirror. The mirror reflects and concentrates the light from the lamp (above the bird-call) upon the piece of white paper, and at the same time reflects and concentrates the sound from the bird-call upon the sensitive flame.

then place a flat mirror so that the sound of the bird-call passes over the flame and is reflected back perpendicularly by the glass. There are now two sets of waves sweeping over the flame in opposite directions; and their combination results in the formation of what are called "stationary waves," waves which rise and fall without moving forward. They may be seen sometimes when waves roll up against a vertical cliff and recoil therefrom. In such cases there are places at regular intervals

where the water does not move up and down at all ; while in between such places the water rises and falls alternately. So in the case where sound-waves and their reflections are travelling opposite ways over the same part of the air, there are places where the air does not move : such places are called "nodes." In between them the air is in motion, vibrating to and fro. For some positions of the flat mirror the flame happens to be in one of the lines where there is no motion, and it does not flare. But if the reflector is moved a little farther away, or a little closer, the jet flares. And if the motion of the reflector is continued the flame is once more silent, then once more noisy, and so on ; it is easy to count forty or fifty such alternations. It is possible to measure the wave length of the sound in this way.

When sound spreads away through air or water or a solid it weakens because it spreads ; but there is also a second cause of weakening, which in some substances is very effective. There is in fact a real loss of energy as the sound tries to go through any substance, and we speak of the "absorption of sound," of "sound-absorbing substances," and so on. The "silent cabinets" for telephones are packed round with felt, or cork dust, or something of the kind : some substance, generally, which is much divided and contains many air-pockets. There is a con-

venient way of studying such effects which we can easily try. Here is a tuning-fork; it is made to vibrate, but is not audible until I stand it upon its proper box. Then the sound rings out loudly. Now let us put various materials between the fork and the box and see if the sound will get through. Wood and metal and such hard things are quite transparent to the sound: even a cork or a piece of rubber transmits a fair amount. A ball of wool does not cut off the sound entirely when the fork is pressed firmly on it. A lump of soft car grease transmits sound quite well. One of the best insulators of all is a pneumatic cushion, and that is why it is a good thing to put an air cushion under your pillow when you are sleeping in the train, or to use a pneumatic tyre when you want to support some apparatus which is to be kept free from vibration.

SOUND IN MUSIC

WE have been thinking of sound as a means of communication or as something which accompanies most movements and gives information about them to ears that listen. To-day we want to consider sound from another point of view. It is a fact that certain sounds and certain successions of sounds are very pleasing to our senses. In order to produce them we make musical instruments. Let us consider some of the simpler rules of construction that must be followed if we are to be able to draw from the instruments the melody and harmony that we like to hear.

The first thing that we have to do is to learn how to make a sound that remains for some time unchanged: that has, as we say, a definite pitch. Perhaps one of the first notes of this kind that

men listened to was the twang of the bowstring; and this may have been the beginning of all the stringed instruments. Let us ask ourselves what is the real distinction between such a steady note and an irregular noise such as the coal-man makes when he empties his sack on the pavement. The one sound is of the kind of which music can be made; nothing at all can be done with the other. I will try to make the difference clear in the following way. If I wave my hand towards you a *pulse travels away in the air at* a great rate, eleven hundred feet a second, as we have already seen, but it makes no impression on your ears. They have no power to detect a single pulse like that. If I were to wave my hand as fast as I could there would still be no resulting sound. But if I could wave it fifty times a second your ears would be filled with a deep booming noise: there must in fact be a sufficiently rapid succession of pulses before the ear hears.

As I cannot myself move anything so quickly

as that, we must have recourse to some mechanical method of carrying out the experiment. Instead of sending a pulse to you by moving my hand, I will cause a pulse to be sent out into the air by suddenly opening a hole behind which is compressed air ready to force itself out into the open. The instrument I am going to use has been called a siren. There is a cylindrical box, in the lid of which are cut small holes out of which the air is to come, and the box is in communication with the organ bellows. Just above the lid is a metal disc which as you see can turn round freely. The disc also is pierced with holes, and, when the holes in the top disc are just over the holes in the lid, air spurts through them all at the same time and makes one of those pulses which are going to be linked

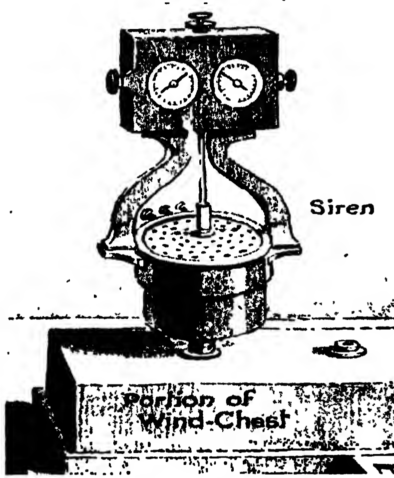


FIG. 17.—This figure shows the siren, with its revolving disc and counting mechanism. The siren stands on a wind-chest. The disc has four rings of holes, any one of which can be set in action by pressing the proper key.

together in a sound. As the disc is made to turn round, the series of holes is alternately open and shut, all of them acting together, and so a set of pulses is sent out into the air in regular succession. When the disc spins slowly you can hear the separate puffs. As a matter of fact, each puff is accompanied by a little whistling noise, such as *always goes with the* issue of compressed air, and that is why you hear anything at all of the individual puff. But of the main shove given to the air your ears are quite unconscious. If I leave the disc alone after giving it a little start and keep up the supply of air under pressure the speed of the disc rapidly increases. That is because the little holes are so cut in a slanting fashion that the issuing air drives the top disc round. Now the important thing to observe is that as soon as the speed increases sufficiently we begin to be aware of a very deep note. As it goes faster and faster the note rises in pitch and finally ends in a shrill scream.

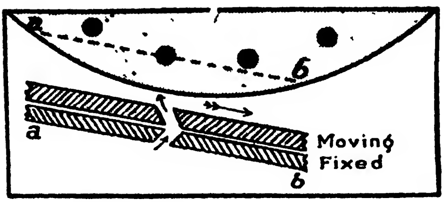
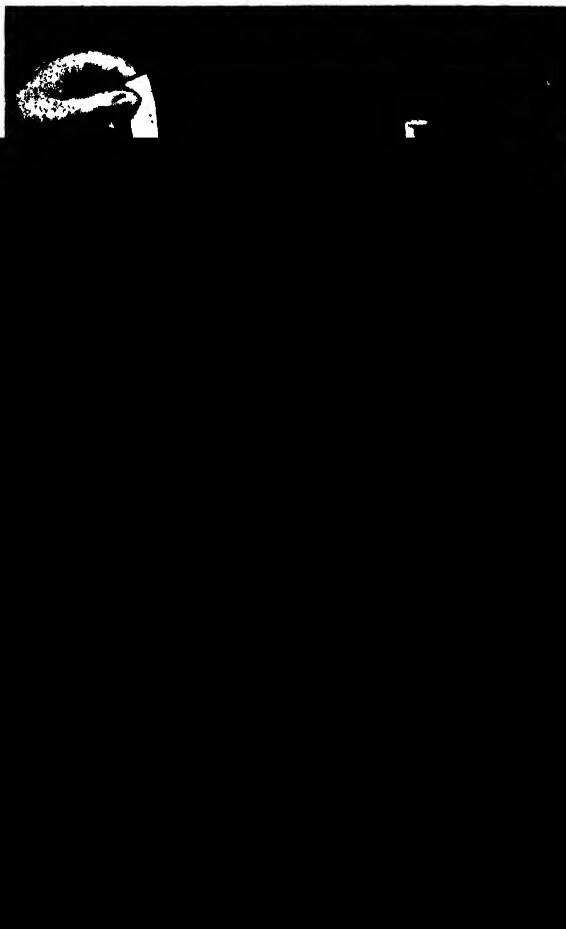


FIG 18.—This figure shows a section of the moving and fixed discs along the line *ab*: the holes in the discs are so shaped that the upper disc is driven round by the blast of air.

It is really because the successive puffs are all like one another, and because they succeed each other sufficiently fast, that the ear hears a sound of definite pitch. We find, too, that the more rapid the succession the higher the note. Here, then, is the whole difference between an irregular noise and a note. We find that in whatever way we make pulses start off in the air, if only the number of them that start off in a second is regular and sufficient, the ear hears a note; and the pitch of it depends on how many there are in a second. If I can arrange for some operation, no matter what it may be, to be repeated two hundred times a second, I shall always get the note of that frequency; and conversely, whenever a note of that pitch is heard, it is quite certain that something or other is being done two hundred times a second. The siren gave that note when it revolved so fast that in every second there were two hundred puffs.

Here is a set of cogged wheels driven by an electric motor. I can hold a card to one of the wheels so that, as it turns, the card flops continually from one tooth to the next. Each time it does so it makes a little disturbance in the air and starts a pulse on its travels. When the wheel turns fast enough, the succession of pulses makes a note which is higher the faster the wheel is turned. When two hundred teeth pass under the

card in the second we get the same note as before. There are eight wheels on the axis of the electro-motor, and the numbers of the teeth on the different wheels are 24, 27, 30, 32, 36, 40, 45, 48. Notice in passing that as they are touched in succession with the card we get the notes of the



all the intervals of the musicians correspond to definite numerical ratios.

When two wheels are geared into one another, as in the gear-box of a motor-car, each time the teeth of one wheel enter and leave the spaces of another, there is a tiny shock which starts a quiver in the metalwork of the car and in turn a pulse into the air. The better made the wheels, the more silent is their play. But there is always a little hum, and the driver instinctively listens to it because it tells him whether the car is running smoothly and whether it is altering its speed. The note of the hum tells how many teeth pass each other in a second. When a motor-car with a studded tyre goes past on a wooden or asphalt pavement, there is often a shrill scream which comes from the tapping of the studs on the road, and the note tells you how many taps take place per second. Here is a piece of ribbed silk. If I draw my finger-nail over it, each time the nail slips into a depression between two of the ridges, it starts a little pulse. This happens many hundreds of times a second, and a shrill sound is caused thereby. I cannot get the same effect from a piece of soft cloth, because the separate little risings and fallings of the finger-nail are only made with sufficient sharpness and intensity on the hard ridges of the silk. So also when two pieces of silk rub together, little shrill sounds are made

with which we are all familiar. When we were very small we may have puzzled ourselves over them. As Stevenson says in his *Child's Garden of Verses*:

"Whenever Auntie moves around,
Her dresses make a curious sound.
They trail behind her up the floor
And trundle after through the door."

In the same way we get a note when we draw the finger across the cover of a book, provided it has a regular succession of ridges and hollows; but when the material has irregular depressions all over it, we have only a "noise," in which we can recognise no pitch. When we tear a piece of calico, the regular successive breaking of the threads causes a corresponding succession of pulses in the air by way of the jerking motions of the material and the hands, and there is a sound of definite pitch, which rises if we tear faster.

In general the sensitiveness to high-pitched sounds weakens with age: it is quite usual to find that old people cannot hear the shrill squeak of a bat. The late Francis Galton was very interested in observing the range of hearing possessed by different ears, and used a specially

high-pitched whistle for the purpose of determining the upper limit. To many people very high sounds are all alike: they can tell that there is a sound, but can assign no pitch to it.

At the extreme low-frequency end of the range of hearing there is a special difficulty in recognising by the ear the existence of a note because the body can actually feel the vibration. When the lowest notes of an organ are sounding in a church, it is often doubtful whether we really detect any sound or whether we merely feel the shaking of the pews.

If, then, I want to make a musical instrument, I must find some mechanism which can conveniently be made to do something over and over again at the rate required for each different note. There are ever so many ways in which this can be done; but there are two or three which have been found far more convenient than the rest. And first we may consider the vibrating string. If we stretch a string between two points, and then, taking hold of the middle, pull it to one side and let go, it swings backwards and forwards for a long time, making hundreds of vibrations, as we call them, before it finally comes to rest. That is the sort of thing we want. It would be no use if when we pulled it aside it stayed where we put it, or even if it slowly went back to its first position. It has to be like a pendulum. When the bob is pulled to one side and let go,

its weight carries it down to the central position, but it does not stop there. The way which it has gathered carries it through, and it climbs up the other side till the effort exhausts its energy, then it falls back again, and so a continual to-and-fro movement is set up. The string, like the pendulum, rushes back to its central position, overswings itself, reaches a limiting position on

Fig. 20.—The upper part of the figure shows the "monochord," which is used for the study of the vibrations of the string. The lower part of the figure shows the form of the string while vibrating.

the other side, recoils, and repeats the motion again and again. It is very important to observe that both string and pendulum take the same length of time over each swing, no matter whether that swing is large or small. Vibrating or oscillating bodies of whatever kind most commonly obey this rule, and it is very fortunate for us that it is so. Suppose for a moment that the rate of vibration altered as the swing diminished.

Imagine trying to play on a piano if the pitch of the note depended on how hard one struck it, and changed as the sound died away!

If the bob of the pendulum is set swinging in water it soon stops, because the energy is given to the water and wasted in little eddies and whirls. When the pendulum swings in the air there are eddies also, but relatively the waste of energy is far less. A vibrating string causes little disturbance in the air, because it is so thin and slips through so easily. Very little of its energy is given out in this way, but as it moves it shakes its supports, and these again anything on which they stand, and all these motions mean a gradual frittering away of the energy of the string.

There is one way in which we particularly want the energy to spread itself, and that is in pulses through the air; in order to get these well under way it is usual to mount one or other of the supports of the string on a broad surface which, when made to vibrate, has a large effect on the air which is in contact with it. This surface is called a sounding-board. If you remember our previous experiment with the musical box you will appreciate its importance. Here is a string (Fig. 21) which is suspended from a bracket on the wall, and is tightly stretched by the large weight attached to it. If it is plucked it vibrates freely,

but there is very little noise. In the case of the monochord the string is mounted on its proper sounding-board: when it vibrates we hear it well.

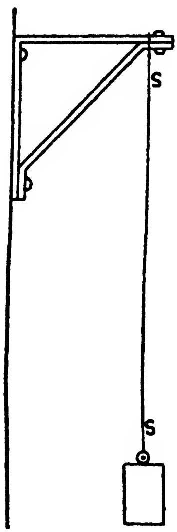


FIG. 21.—This string when made to vibrate does not give out much sound: it is not mounted on a "sounding-board."

The sounds that you hear when a violin is played come really from the body of the violin, not from the strings; and because the body is apt to alter the quality of the notes which originally come from the string, and because it is the interpretation given by the body which you really hear, therefore the body has to be made most carefully, and a first-class violin is a great treasure. Strings must be good, of course, but it is not the strings which are costly.

Here, again, is a tuning-fork (Fig. 22). When it is made to vibrate it is comparatively silent unless its stem is pressed upon some surface which it can set into vibration so that strong pulses can be sent out into the air. It is sometimes mounted on a sounding-box of such a form as to be highly efficient for the purpose of launching the sound.

A string, then, gives a continuous note in a very convenient way. Notice too that we have the pitch of the string quite under command. We can raise the pitch either by shortening the string or

by stretching it more tightly; both effects are readily shown on the monochord. But a musical instrument must be capable of giving out, not one, but many notes, and when we take the string as the basis of construction we must in some way arrange that the player shall have many strings at his command, or at least be able to produce all the notes he wants from a limited number of strings. The violinist uses four strings only, and makes the different notes by placing his fingers on one or more of them at different points, thus artificially altering their length. He holds the string down firmly with his finger so that the vibrating portion reaches from that finger to the bridge. All the responsibility of getting the right note is thrown on the player himself. That is the way to obtain the finest, most delicately shaded results.

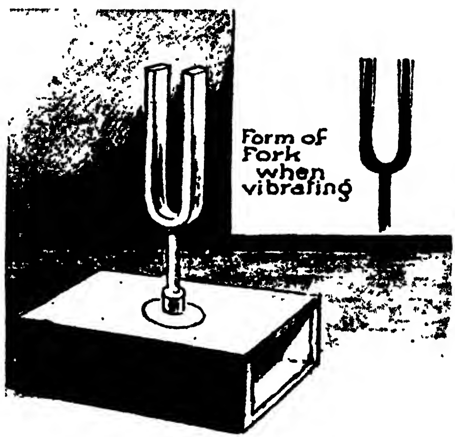


FIG. 22 A Tuning-Fork, mounted on its proper sounding-box.

In the piano and harp a different string is pro-

vided for every note that is required. In one way the task of the player is very much lightened, but at the same time he loses the power of making certain minute changes in pitch which are required, as we shall see later, for perfect music.

Any changes of pitch which are required to put a stringed instrument into tune before playing are, of course, made by altering the tensions of the strings concerned.

There is yet one other method of obtaining several notes from one string which we can explain by means of the monochord. I draw the bow across the string and bring out the lowest note which it can give. If now I touch the string in the centre and bow again, I get a note which is an octave higher. On examining the string closely it is easy to see that each half of the string is now vibrating separately. We have already learnt that when one of two notes is an octave above the other it makes twice as many vibrations each second; and so the half string vibrates twice as fast as the whole string. There is another point to be observed. If I do not touch the string exactly in the middle, I get no good note at all—only a horrible groan, which shows that the string does not care to vibrate in that way. It is easy to see why. The string can vibrate in two equal vibrating parts, because in that case the two will always vibrate at the same rate and will always

pull against each other in exactly opposite directions at the point of division between them. This is necessary if the point is always to be kept at rest. If the parts were unequal, the string would have to get sometimes into the shape shown in the figure, which would be impossible. The lightest touch at the centre will make the string vibrate in two equal parts: it is quite a natural form of vibration We call the lowest note, which is that given by the whole string vibrating together, *the* note or tone of the string; we call this new note an overtone.

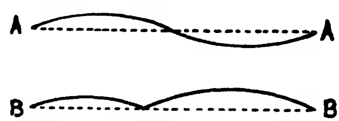


Fig. 23.—*AA* represents a momentary form of a string which is vibrating in two equal parts. A string could not vibrate in two unequal parts because it would then have to take, at intervals, the form BB; which would be impossible.

In just the same way if we touch the string exactly at one-third of the distance from one end, and draw the bow across it, we can make the string vibrate in three equal parts. The note then given is recognised by the musical ear as the fifth of the note corresponding to the division into two. From the toothed wheel apparatus we can satisfy ourselves that whenever two notes are a fifth apart the upper has three vibrations or pulses to the lower's two; we infer that each part of the string divided into three makes three

vibrations, in the same time that each part of the string divided into two parts makes two vibrations. And so we go on to higher numbers : it is easy to

FIG. 24.—Showing half the riders in the act of being unseated. Those unshaken are at the Nodes or Points of Rest.

get notes making 4, 5, 6, etc., up to 12, 13, or more times the vibrations of the bottom note in each second. So we can get many notes from one string.

There is a beautiful little experiment which

illustrates the division into parts. Let us show, or example, the division into four. I put riders of blue paper on the string at the first and second points of division of the string into four, leaving the third point of division to be touched by my finger. Half-way between the end of the string and the first point, and between the first and second points and between the second and third, I mount riders of yellow paper. When the string vibrates in four parts the points where the blue papers are riding are points of rest; but, where the yellow papers are, there will be the movement of the vibration of the string So when I put my finger on the right spot, and just give the slightest touch with the bow, all the yellow papers are thrown off but the blue stay where they are.

A second very important class of musical instruments is based on the movements of columns of air contained in tubes, or of masses of air contained in vessels of any form. For instance, here is a tall jar (see later, Fig. 28); the air inside it may be set into vibration, swinging in and out of the jar at a rate which depends mainly on the length of the jar. In the case of the string we started the vibrations by pulling the string to one side and letting go, after which the string continued to vibrate and radiate sound for some time. We cannot do the parallel experiment with an air column; or rather we cannot do it so successfully. To show how much can

be done, I take a set of test-tubes, some containing water, some nearly empty, arranged in the order [redacted]

lasts long enough for you to get an idea of pitch nevertheless.

When the water is poured out from a full bottle, the gurgling noise consists of a succession of short-lived notes: it is readily observed that they fall in pitch as the air-space becomes larger Noise is made, too, when the bottle is filled again; and in this case the pitch rises with the diminishing air-space, as we have occasion to observe often enough whenever, for example, a jug is filled at a tap.

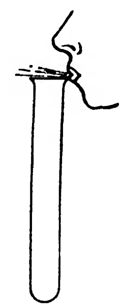


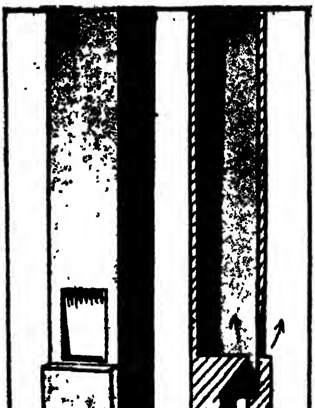
FIG. 26.—Blowing across the mouth of a tube sets the air column into vibration.

It is just as easy to get a variety of notes with these vibrating air masses as it was with the strings. We have to use long columns or large masses of air to get the deep notes, and short columns or small masses to get the high notes.

If we want to make a continuous note with a mass of air we must do something more than give it a single shock, we must keep the note going. There are ever so many ways of doing this, some of which we must look into carefully. Sometimes we blow across the mouth of the tube or body of air. I will explain later how that may set the air in the flask or tube in vigorous and continuous vibration. For the present it is enough to give examples. When I blow across the mouth of the

test-tubes, it is easy to get a response which gives the same notes as we got when the corks were drawn. By blowing in the right way, loud notes can be obtained.

In organ-pipes and whistles there are channels



to guide the air up to and across the mouth of the pipe, so that the player cannot make a mistake; the flute and the fife leave the player to do the directing of the stream himself, and that is why it takes a little practice to get the proper sound out of them. When we make

[redacted]